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Opportunities for and Challenges to Further Reductions in the "Specific Power" Rating of Wind Turbines Installed in the United States

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Short title: Understanding "Specific Power" Trends in the United States

Keywords: specific power, LCOE, capacity factor, turbine design, long blades, large rotors, economics, geospatial modeling

Abstract

A wind turbine's "specific power" rating relates its capacity to the swept area of its rotor in terms of W/m^2. For a given generator capacity, specific power declines as rotor size increases. In land-rich but capacity-constrained wind power markets, such as the United States, developers have an economic incentive to maximize MWh per constrained MW, and so have favored turbines with ever-lower specific power. To date, this trend toward lower specific power has pushed capacity factors higher while reducing levelized cost of energy (LCOE). We employ geospatial LCOE analysis across the United States to explore whether this trend is likely to continue. We find that under reasonable cost scenarios (i.e., presuming that logistical challenges from very large blades are surmountable), low-specific-power turbines could continue to be in demand going forward. Beyond LCOE, the boost in market value that low-specific-power turbines provide could become increasingly important as wind penetration grows.

Introduction

The design of modern wind turbines has evolved significantly over time. Although three-bladed, upwind turbines emerged as the dominant archetype as far back as the late 1980s, this configuration has since undergone numerous design improvements that have contributed toward greater reliability, increased energy capture, and lower costs. Well-known examples of such enhancements include variable-speed turbines, individual blade pitch, and dedicated airfoils with passive load-shedding capabilities.

No less important, wind turbines have also grown physically larger in several key dimensions, including rotor diameter, tower or hub height, and nameplate capacity. There is widespread acknowledgement that this wind turbine scaling has been a primary driver of historical reductions in the levelized cost of land-based wind energy (EWEA, 2009; Lantz et al., 2019; Wiser et al., 2011), by lowering investment costs per unit of capacity, boosting wind plant production, and reducing operations and maintenance (O&M) costs. Growth in turbine size has been enabled by scientific and engineering advancements, as well as enhanced computational tools, controls software, design standards, manufacturing methods, and O&M procedures (Wiser et al., 2011).

In addition to scaling, wind turbine design has become more closely tailored to the specific market conditions where the technology is being deployed, including the applicable wind regimes, land-use patterns, grid accessibility, and policy environments. In the United States in particular, but also in other countries like China, India, and Brazil, one manifestation of this local optimization has been a trend toward lower "specific power" ratings. Specific power is defined as the ratio between a turbine's nameplate capacity and the swept area of its rotor, and is expressed in units of watts of capacity per square meter of swept area (W/m^2). Because swept area increases with the square of blade length (i.e., πr^2), mounting longer blades on a turbine with fixed generator capacity reduces that turbine's specific power rating. Hence, this trend toward lower-specific-power turbines is most visible through increasingly longer blades and greater swept area relative to nameplate capacity.

Lower-specific-power turbines have a number of attributes that have driven their deployment in the United States and many other markets around the world. Most obviously, for a given turbine generator capacity, a larger rotor captures more of the energy in the wind flowing past the turbine at any given moment, and therefore runs the generator closer to or at its rated capacity a greater percentage of the time. The result is more megawatt-hours (MWh) of electricity generated per megawatt (MW) of capacity installed, resulting in a higher "capacity factor."[1]

A higher capacity factor is not necessarily an end design goal in and of itself. However, with the sophisticated control systems of modern turbines, extending blade length to increase energy production can often be achieved with relatively limited impact to the rest of the turbine system (e.g., nacelle, tower, foundation). As a result, larger rotors are often incorporated with a limited impact on overall turbine cost on a per unit capacity ($/MW) basis. In such cases, boosting capacity factor allows for greater energy production per invested dollar and provides a direct path towards a lower levelized cost of wind energy ("LCOE," expressed in $/MWh). This is particularly true in the United States and other relatively land-rich countries (e.g., China), where wind projects tend to be constrained more by contractual, interconnection, or transmission capacity limits rather than by land availability. Under these conditions, turbine manufacturers and plant owner/operators have an incentive to maximize MWh generated per installed—and constrained—MW of capacity. In other markets with land constraints but robust transmission networks (e.g., much of Europe), turbine designers and plant owners may instead prefer to maximize capacity and energy produced per unit land area, resulting in a preference for greater generator capacity and relatively higher-specific-power turbines.[2]

The energy generation profiles that result from lower-specific-power turbines (as well as taller towers) have also been found to have the knock-on effect of improving the wholesale market value of wind energy (Molly, 2011). Research shows that the marginal value of wind energy to the electric grid declines with increasing wind penetration, as greater amounts of wind generation flow onto the grid concurrently during windy periods, thereby depressing wholesale power prices (e.g., Hirth, 2013; Mills and Wiser, 2014). By having power curves that more-evenly distribute when wind generation occurs—e.g., relatively less-generation during high wind hours and relatively more generation during low-wind hours—turbines with lower specific power and taller towers can partially mitigate these declines.

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[1] Capacity factor is defined as the ratio between the actual amount of electricity generated over a given time period and the maximum amount of electricity that could have been generated over that same time period if the generator had been running at full capacity the entire time.

[2] Maximizing wind generation per unit land area ideally involves maximizing *both* the amount of wind capacity that will fit on the site *and* the MWh generated per MW of installed capacity (e.g., by installing as large of a rotor as possible). In practice, however, physical limitations on blade size (e.g., due to manufacturing and/or transportation constraints, as well as turbine loading considerations) generally result in higher-capacity turbines also having relatively high specific power ratings.

Specifically, a range of studies finds that at high wind penetrations, such turbines can boost the grid-system value of wind energy by 8–30% (~$3–15/MWh) (Dalla Riva et al., 2017; Hirth, 2016; Hirth and Müller, 2016; Johansson et al., 2017; May, 2017). Conceptually, this finding is a function of increased wind generation during periods of relatively lower wind speeds, which are, in some markets, at least partially correlated with higher electricity prices.

Despite their potential benefits, lower-specific-power turbines involve trade-offs. Operating a greater percentage of time at a turbine's rated capacity results in spilling energy that could otherwise be captured with a larger generator. Rather than further increasing rotor swept area, boosting the generator capacity can also be a cost-effective way to increase annual electricity production and—particularly if achieved with limited impact to cost per unit capacity—reduce LCOE. Longer blades may also experience greater physical loads and transfer them to the rest of the turbine, perhaps with implications for tower and foundation design and cost as well as long-term reliability. Although, to date, wind turbine manufacturers have—through use of innovative design, sophisticated controls, and new materials—been able to stay ahead of mass and cost curves that compromise the economics of scaling (Garrett and Rønde, 2011a, 2011b; Razdan and Garrett, 2015a, 2015b, 2018a, 2018b), the extent to which they will be able to do so going forward is uncertain (Sieros et al., 2010). Moreover, additional growth in turbine size may be limited by not only engineering and materials usage constraints, but also by social acceptance and regulatory hurdles as well as the logistical constraints and costs of manufacturing, transporting, and erecting ever-larger blades, towers, and nacelle components by road and rail (Cotrell et al., 2014; DNV GL, 2019; U.S. Department of Energy [DOE], 2015a; McKenna et al., 2016).

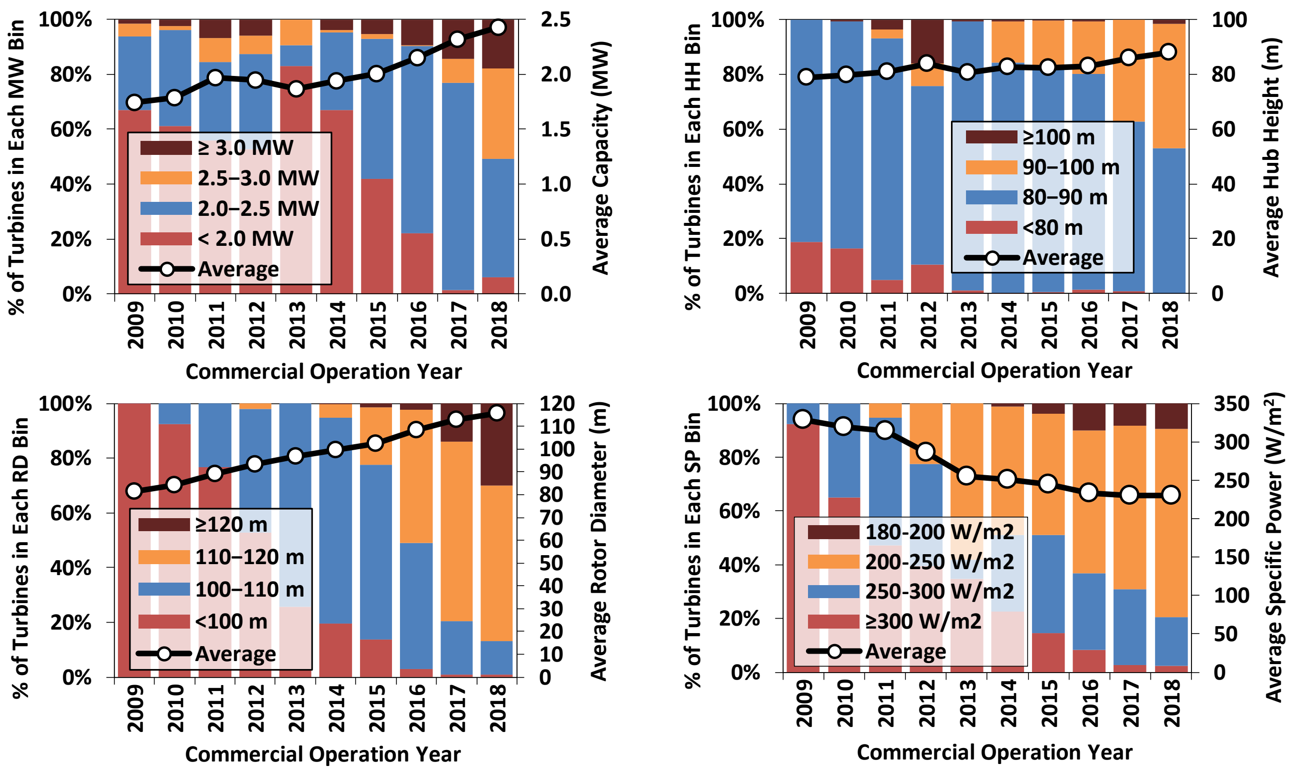
In part because of these tradeoffs, the extent to which this recent trend toward lower-specific-power turbines will continue is far from certain. Further upward scaling in turbine size is anticipated, but uncertainty remains on both the magnitude and relative focus (e.g., rotor vs. generator vs. tower) of that scaling (Wiser et al., 2016; Wood Mackenzie, 2018). Research demonstrates that taller towers and larger rotors can potentially enable economic wind development in lower wind-speed areas that have not seen much or any development to date (Burt et al., 2017; Capps et al., 2012; DOE, 2015a; Lantz et al., 2019; Rinne et al., 2018). But in more-seasoned wind development areas with better wind resources, recent product offerings from the major turbine manufacturers, as well as various analyst projections, suggest that the next concerted move in turbine design will be toward higher-capacity turbines, which—given the current limits on blade length—will have higher, not lower, specific power ratings.

This article examines the trade-offs posed by low-specific-power turbines, particularly with an eye toward evaluating the opportunities for and challenges to continued specific power reduction in the future. Using empirical data, we document the historical trend toward lower-specific-power turbines in the United States, and link that trend with higher capacity factors and lower LCOE. We also review recent research out of Europe that finds that a lower specific power rating can increase the value of wind generation in the wholesale market, particularly under high-wind-penetration scenarios. Next, in light of the trade-offs involved, we discuss the extent to which this trend toward lower specific power is likely to continue in the United States. This discussion is informed by geospatial analysis that explores the relative economic attractiveness of several different wind turbine designs—including low-, business-as-usual (or reference), and high-specific-power turbines—across the United States. As explained in more detail later, the geospatial analysis relies on wind speed data from the National Renewable Energy Laboratory (NREL) Wind Integration National Dataset (WIND) Toolkit in order to quantify the capacity factors associated with these three turbine configurations at 2-km grid resolution across the continental United States. We then couple these capacity factors with varying estimates of up-front installed costs, as well as fixed assumptions about operating expenses and financing terms, to yield countrywide estimates of the LCOE of each turbine configuration under three different cost scenarios. The purpose is to evaluate the cost conditions under which higher- or lower-specific-power turbines might prevail in terms of LCOE, given their relative capacity factors.

In the end, although the continuation of this trend towards lower specific power is in no way assured, this analysis suggests that under reasonable cost scenarios, low-specific-power turbines could continue to be an important part of the United States fleet going forward, particularly as wind penetration increases (thereby eroding the market value of wind) and in lower-wind-speed regions of the country.

Historical Trends, Drivers, and Impacts of Low-Specific-Power Turbines in the United States

This section documents the historical trend toward the deployment of lower-specific-power turbines in the United States, as well as the drivers and impacts of this trend. Figure 1 shows the annual averages and distributions of nameplate capacity, hub height, rotor diameter, and specific power of utility-scale (i.e., >100 kilowatts [kW]) wind turbines installed in the United States over the past decade. The trend toward greater capacity turbines with larger rotors and lower-specific-power ratings is clear: the average nameplate capacity increased from 1.74 MW in 2009 to 2.43 MW in 2018, while the average rotor diameter grew from 81.5 to 115.6 meters (m) (pushing the average swept area from 5,200 m^2 to 10,500 m^2), reducing the average specific power rating from 329 W/m^2 to 230 W/m^2.



Source: Wiser and Bolinger, 2019

Figure 1. Trends in turbine capacity, hub height (HH), rotor diameter (RD), and specific power (SP)

Figure 2 highlights the comparative differences in the growth of these four parameters, along with the swept area of the rotor. Growing at the square of blade length, the average swept area has doubled since 2009, greatly outpacing the 40% increase in nameplate capacity. As a result, average specific power has declined by roughly 30%.

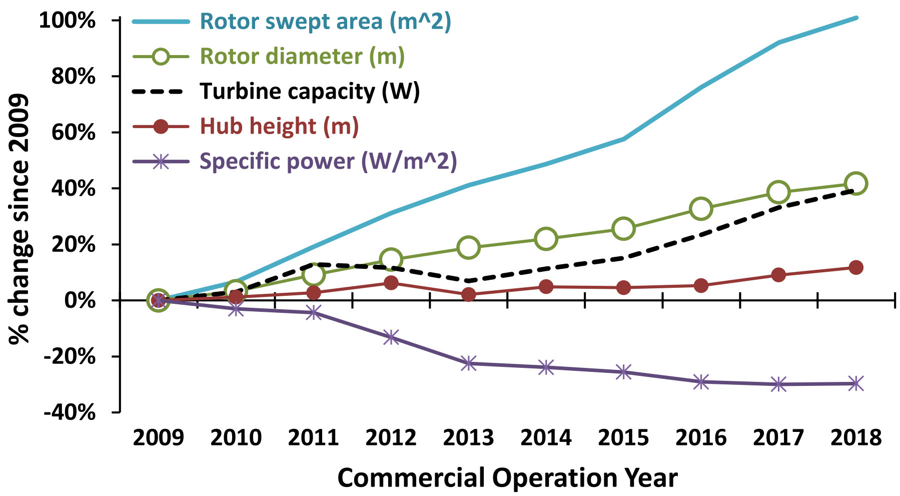
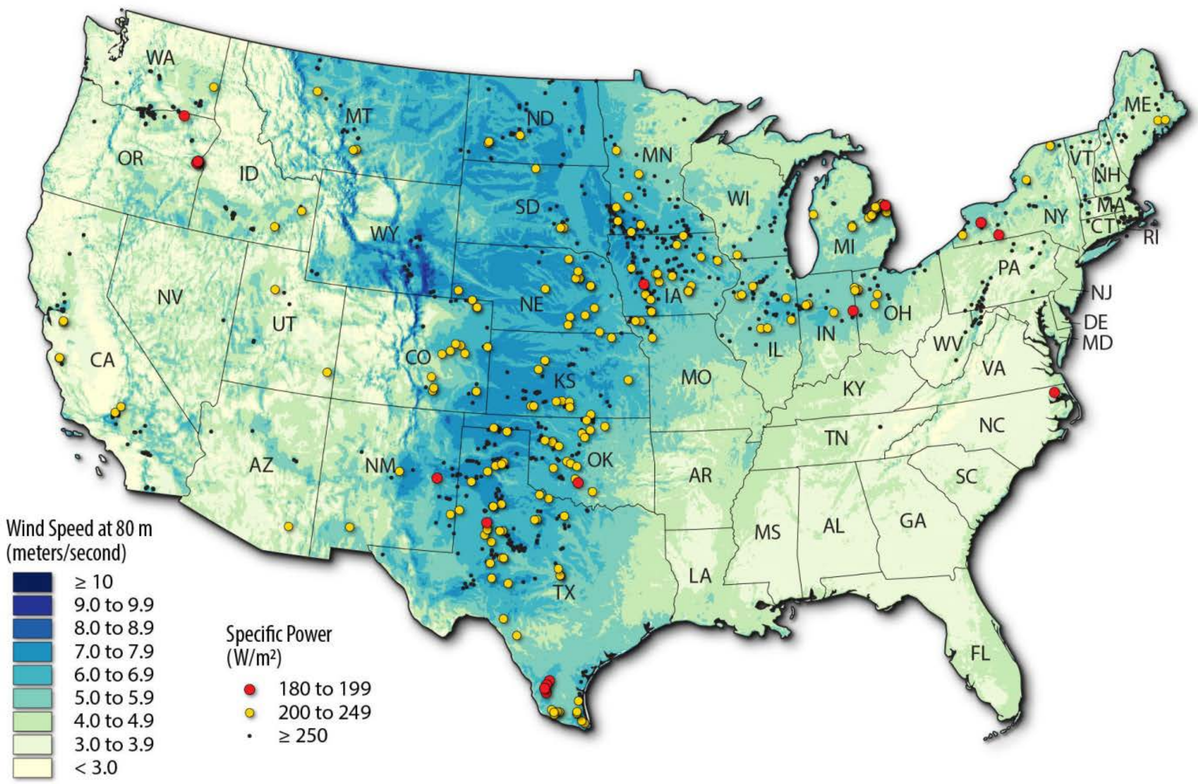


Figure 2. Cumulative percentage change in key turbine parameters since 2009

Though initially targeted at lower-wind-speed sites, low-specific-power turbines have since been deployed more broadly in the United States—in some cases even at high-wind-speed sites. For example, Figure 3 shows that by the end of 2018, projects with specific power ratings of less than 250 W/m^2 (yellow dots) were widespread throughout the United States, with a number of projects under 200 W/m^2 (red dots) operating in the high-wind-speed areas of Texas, New Mexico, Oklahoma, and Iowa (among other places). In many of these cases, a combination of relatively high site elevation (i.e., with lower air density), relatively low wind turbulence, and the capabilities of sophisticated control systems provides sufficient comfort to turbine engineers and manufacturers, as well as project developers and sponsors, that these low-specific-power turbines can withstand higher wind speeds than might have been intended by initial turbine design.



Source: Wiser and Bolinger, 2019

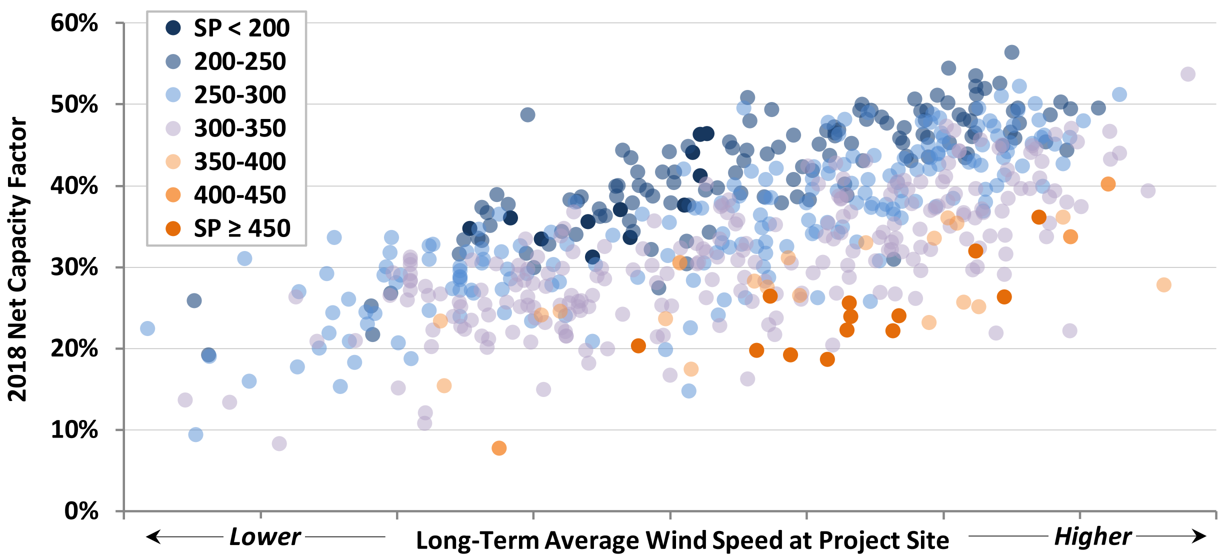
Figure 3. Map of wind project location and specific power overlaid on long-term average wind speed as estimated based on typical meteorological year conditions for the period of 1997-2010

Although the United States has been a market leader in terms of deploying low-specific-power turbines, it is not alone. China and, more recently, India and Brazil, have increasingly deployed turbines with similarly low-specific-power ratings. This stands in contrast to most European countries, where average specific power remains higher (while similarly trending downward in recent years, but from a higher level). Though it is difficult to generalize, the distinction between these two camps seems to be those countries with ample land area but constrained transmission (i.e., the United States, China, India, Brazil) and those with stronger grids but constrained land area (i.e., Europe).[3] The "capacity-constrained" camp has an incentive to maximize the MWh generated per (constrained) MW installed—e.g., by reducing specific power—while the "land-constrained" camp has an incentive to maximize the amount of capacity installed and MWh generated per (constrained) land area, which often results in higher-capacity, higher-specific-power turbines (in light of manufacturing and transportation constraints on blade length).[4]

[3] Interconnection and transmission limits are not the only potential constraints on project capacity—policy can also play a role. For example, in the United States, the Public Utilities Regulatory Policy Act of 1978 requires utilities to purchase generation from "qualifying facilities," including wind projects, that are up to 80 MW in capacity. As a result, there are many 80 MW wind projects in the United States.

[4] Another potentially important differentiator between the United States and other countries with respect to specific power is the federal production tax credit (PTC) for wind power in the United States. The PTC is a 10-year income tax credit that, like any other "per-MWh" source of revenue (e.g., a power purchase agreement or feed-in tariff), financially rewards the maximization of MWh per installed MW. One key difference between the PTC and these other revenue sources, however, is that the PTC—as a tax credit rather than cash—is not readily fungible, and so must often be monetized by specialized third-party "tax equity" investors. In exchange for the project's

As such, in capacity-constrained markets like the United States, the trend toward lower-specific-power turbines has been driven by a desire to maximize MWh (and therefore revenue) per constrained MW through a higher capacity factor, leading to a lower LCOE. The industry's ability to achieve higher capacity factors through lower specific power is demonstrated in Figure 4, which shows project-level capacity factors in 2018 from 614 projects totaling 63.2 gigawatts (GW) that were installed in the United States from 2009 to 2017. Clearly, the quality of the site (as denoted by the long-term average wind speed along the x-axis) matters for capacity factor, but so too does specific power: for any given wind speed, those projects using the lowest-specific-power turbines tend to have the highest capacity factors, and vice versa.

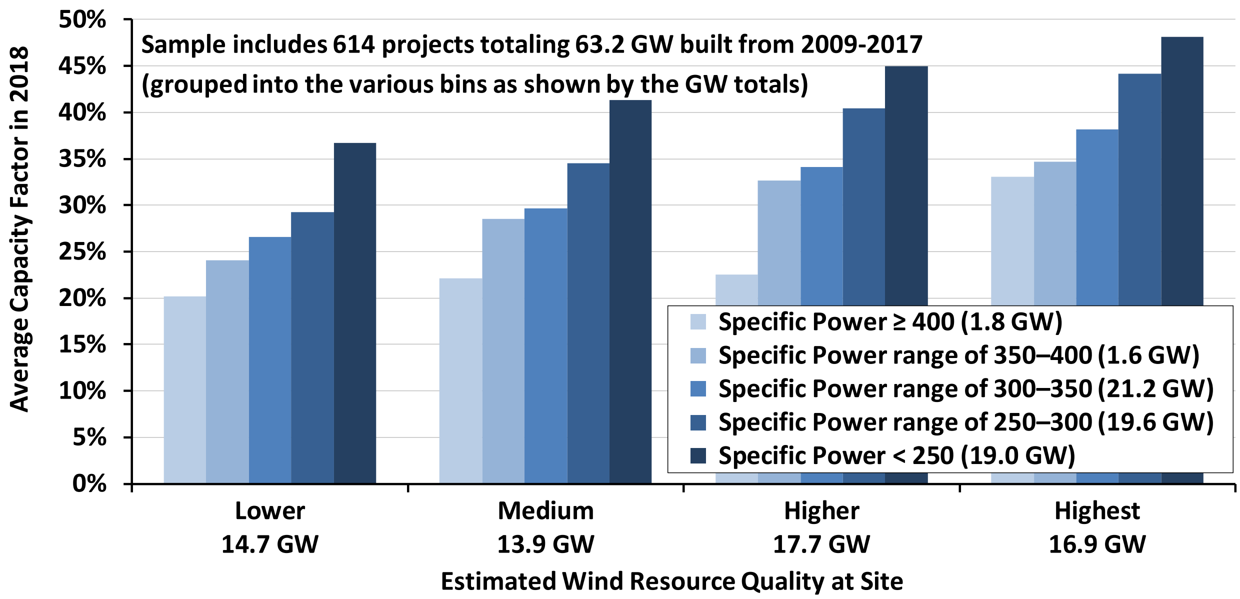


Source: Wiser and Bolinger, 2019

Figure 4. Capacity factor in 2018 as a function of long-term average wind speed and specific power

This relationship is even more evident after binning the empirical data from Figure 4 for both wind speed and specific power, to reduce some of the inherent noise in the project-level data. In Figure 5, not surprisingly, the average capacity factor of virtually every specific power bin increases when moving from a lower- to a higher-wind-speed bin along the x-axis. More notable, though, is that within any of the four wind-speed bins, moving from higher- to lower-specific-power turbines provides a similar or greater increase in capacity factor.

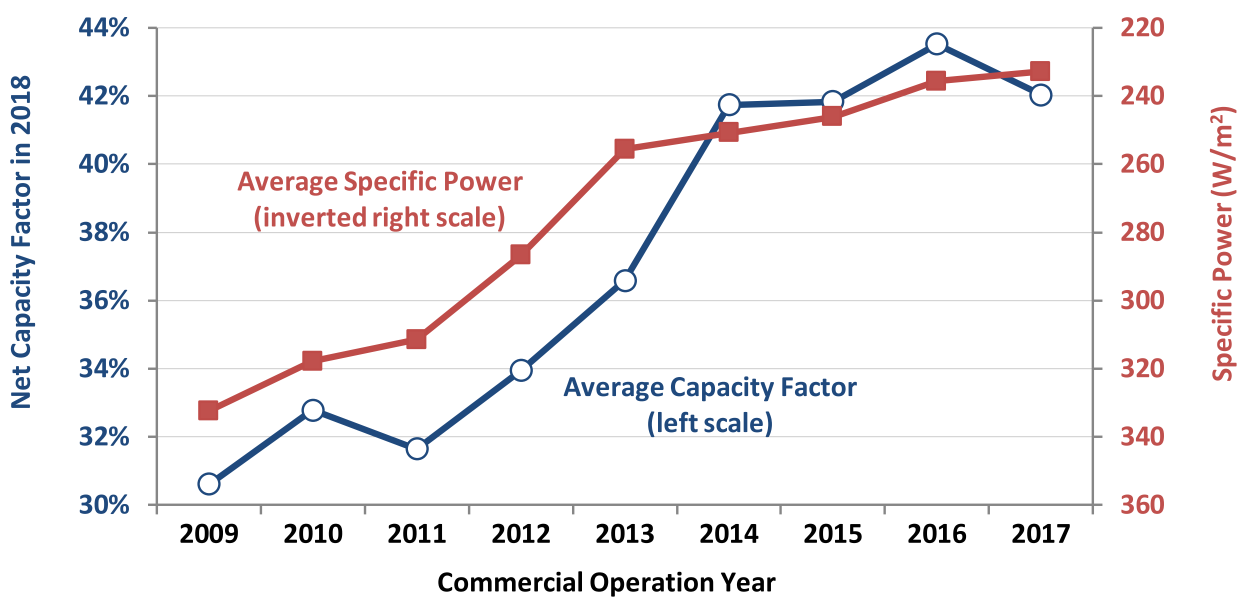
PTCs, these tax equity investors typically provide 45–75% of the capital required to build the project, and then often drop out of the project after the 10-year PTC period has ended. This common financing structure in the United States—where tax equity investors provide the majority of up-front capital but only have an interest in the project during its first 10 years—may create an economic incentive to maximize generation, and PTCs, in the first decade of the project's life (e.g., via low-specific-power turbines), even if potentially at the expense of performance during the second decade (e.g., if there do happen to be any long-term O&M implications from mounting ever-larger rotors on fixed generators). Though rather speculative, and also mostly outside of the scope of this paper, this notion that tax credits and financing structures might also be a driver of lower-specific-power turbines in the United States is nevertheless worth mentioning here in this footnote, if only because none of the other major wind markets—e.g., none of the European countries—support wind power through the tax code like the United States does.



Source: Wiser and Bolinger, 2019

Figure 5. Capacity factor in 2018 as a function of binned wind speed and specific power

The time trend is also instructive. Drawing upon the same wind project sample as Figures 4 and 5, Figure 6 shows the average specific power of turbines deployed each year in the United States since 2009 (red line)—in this case, plotted on an inverse scale so that specific power moves directionally with capacity factor (the blue line). Although averages mask geospatial variations in both specific power and capacity factor over time, in general there is a strong correlation between the decline in average specific power and the increase in the average capacity factor in 2018 among more-recent project vintages.

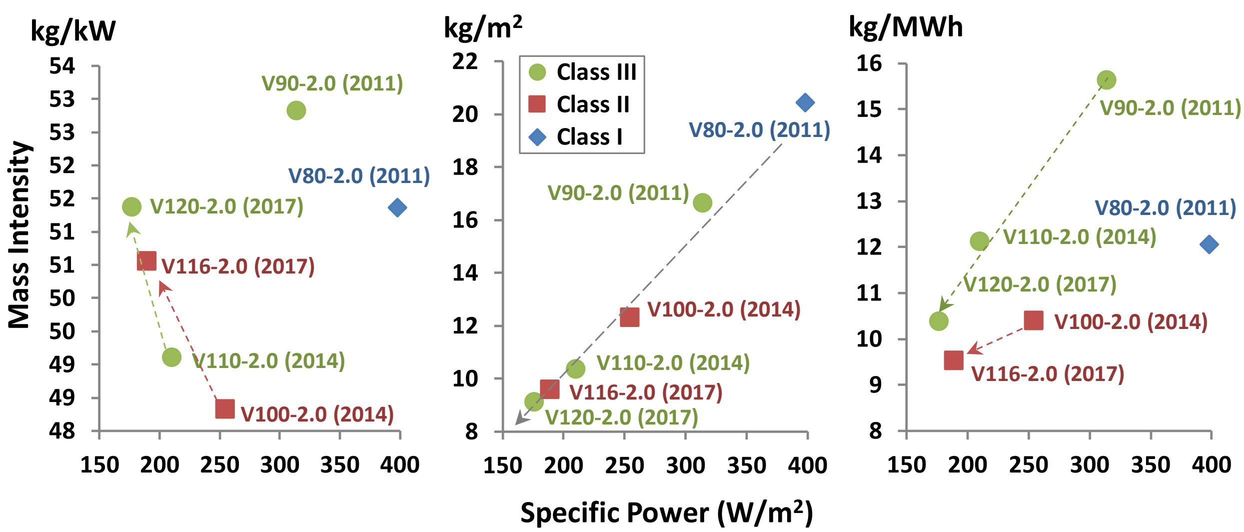


Source: Wiser and Bolinger, 2019

Figure 6. Average specific power and capacity factor by project vintage

Of course, a higher capacity factor is not necessarily an end goal itself, particularly when there is a cost to achieving it—in this case, the cost of mounting a larger rotor on a given turbine. Moreover, due to the "square-cube law," the cost of a larger rotor extends beyond just the immediate first-order effects. The square-cube law states that as the diameter of a wind turbine's rotor increases, theoretical energy output increases by the square of the rotor diameter, but the volume and mass of material required to scale the rotor increases as the cube of the rotor diameter, all else being equal (Burton et al., 2001). Consequently, at some size, the cost of a larger turbine will increase faster than the resulting energy output and revenue, making further size increases uneconomical (Sieros et al., 2010).

To date, the wind industry has been able to avoid uneconomical scaling-related cost increases by streamlining manufacturing operations, optimizing turbine design, and using fewer, lighter, and stronger materials (Garrett and Rønde, 2011a, 2011b; Razdan and Garrett, 2018a, 2018b, 2015a, 2015b; Wiser et al. 2011). Figure 7 employs mass data sourced from Vestas' life-cycle analyses of its 2.0 MW platform in order to plot how mass intensity (expressed three ways, from left to right: in kg/kW, kg/m^2 of swept area, and kg/MWh) has changed with specific power over time.[5] Expressed in kg/kW, mass intensity has generally (and not surprisingly, given the static 2.0 MW turbine capacity) increased with longer blades. To the extent that mass can be considered a loose proxy for cost, this increase in kg/kW as specific power declines should push turbine costs higher on a $/kW basis. When expressed in either kg/m^2 or kg/MWh, however, mass intensity within each turbine class *declines* with specific power, enabling lower $/MWh costs. In this way, scaling-related cost increases can still be economical, by enabling lower LCOE and power purchase agreement (PPA) prices.



Source: Garrett and Rønde, 2011a, 2011b; Razdan and Garrett, 2018a, 2018b, 2015a, 2015b

Figure 7. Mass intensity of Vestas 2.0 MW turbines as a function of specific power

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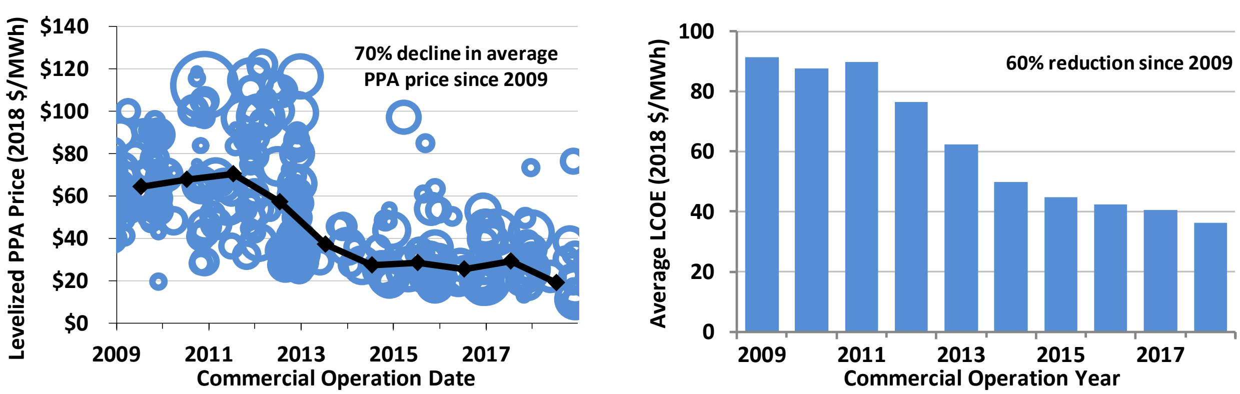
[5] The mass numbers in Figure 7 include only the mass of the rotor and nacelle, and exclude the mass of the tower and foundation, solely because the life-cycle analyses from which the mass numbers are sourced (Garrett and Rønde, 2011a, 2011b; Razdan and Garrett, 2018a, 2018b, 2015a, 2015b) assume different tower heights for different turbines, resulting in an apples-to-oranges comparison. When expressing mass intensity in terms of kg/MWh, we assume hourly wind profiles with three different average wind speeds, as appropriate for each International Electrotechnical Commission turbine class—10 m/s for Class I, 8.5 m/s for Class II, and 7.5 m/s for Class III—to run through the respective power curves.

Progressing from mass intensity to cost, analysis by DOE (2015b), Moné et al. (2015), Stehly et al. (2017), and Wiser et al. (2012) suggests that, at least historically, a reduction in specific power of 100–125 W/m^2 (i.e., between International Electrotechnical Commission [IEC] certified Class I and Class III turbines) can plausibly push turbine costs higher by \$200–\$300/kW. Similarly, Bloomberg New Energy Finance (2019) estimates that for a smaller specific power differential (i.e., approximately 40–50 W/m^2) between IEC certified Class II and Class III turbines, an approximately \$100/kW cost differential could be observed in pricing data through 2018. Finally, analysis of the project-level installed cost data for projects in the United States from Wiser and Bolinger (2019) suggests a somewhat smaller premium, ranging from \$90 to \$170 for a 100 W/m^2 reduction in specific power.

Although the precise cost differentials between low- and high-specific-power turbines remain both uncertain (given the ranges noted in the previous paragraph) and perhaps also variable (e.g., based on supply and demand for specific turbine platforms), the scaling-related cost increases experienced to date have seemingly not been enough to outweigh the LCOE benefit derived from the corresponding increase in generation. This is evident in not only the deployment trends shown earlier, but also when running the respective cost and capacity factor differentials through a simple LCOE calculator. For example, using the assumptions for operational expenditures and financing terms described later, a 100 W/m^2 reduction in specific power that increases capital expenditures (CapEx) from \$1400/kW to \$1600/kW (i.e., within the range of incremental costs from the previous paragraph) will still yield a lower LCOE with just a four percentage point boost in capacity factor (i.e., from 36% to 40%—conservative based on the range of empirical capacity factor increases shown earlier in Figures 4–6).

By enabling a lower LCOE—even with a higher up-front cost—the trend toward lower-specific-power turbines has been one important driver of the broader trend toward lower PPA prices and LCOE in the United States over time. Figure 8 shows that these two metrics have declined on average by 60–70% since 2009.



Source: Wiser and Bolinger, 2019

Figure 8. Trends in PPA prices and LCOE by project vintage (bubble size corresponds to PPA capacity)

Of course, cost is only one side of the coin, with market value being the other. Here again, lower-specific-power turbines appear to offer meaningful benefits, generally providing greater wholesale market value (i.e., energy and capacity value) than higher-specific-power turbines by shifting generation from high wind hours—when local wholesale power prices are more likely to be depressed by an inrush of wind generation—to lower wind hours, when there is generally less wind generation on the system and wholesale power prices are, therefore, likely to be higher.

Recent research out of Europe, summarized in Table 1, corroborates the boost in market value provided by turbines with lower-specific-power ratings (and higher hub heights). At low levels of market penetration, with not enough wind on the system to depress wholesale power prices during windy periods, most of these studies find little or no incremental market value provided by taller, low-specific-power turbines. But above 5–15% wind penetration—i.e., the range in which the United States currently finds itself—these turbines begin to provide incremental market value that grows commensurate with market penetration. At penetration levels of 30–50%, these studies find that, by shifting generation from higher to lower wind-speed hours (via a power curve that cuts in at lower wind speeds), taller turbines with lower-specific-power ratings can boost market value by 8–30% ($3–$15/MWh), depending on the scenario.

Table 1. Studies find that lower specific power can boost market value at high wind penetrations

Report Citation	Wind Value Increase		Specific Power (W/m^2)		Hub Height (m)		Wind Penetration Analyzed
	%	$/MWh	Start	End	Start	End	
Dalla Riva et al. (2017)	8%	2.9	325	250	100	125	varies by country
	13%	4.8	325	175	100	150	
Hirth and Muller (2016)	15%	9	472	211	90	120	30%
	23%	14	472	100	90	120	
Hirth (2016)	12–14%	6.5	568	289	90	120	30%
May (2017)	14%	11	630	200	80	140	50% (all renewable energy)
Johansson et al. (2017)	20%	11	200	100	100	100	40%
	30%	15	300	100	100	100	

This body of research suggests that, in the future, the boost in market value provided by lower-specific-power turbines could become an increasingly significant selling point, presuming that wind penetration continues to increase.

Looking Ahead

Wind turbines with lower specific power have provided tangible benefits to date—primarily via a higher capacity factor achieved at a cost that has enabled LCOE to decline, but also increasingly in the form of enhanced market value. However, questions persist with respect to whether this trend will continue—or potentially even reverse—going forward.

Simple linear extrapolation of the historical trends shown in Figure 1 suggests that, by 2025 under a "business-as-usual" scenario, the average nameplate capacity of land-based wind turbines installed in the United States could increase to 3.0 MW (up from 2.43 MW in 2018), while the average rotor diameter could grow to 139 m (up from 116 m in 2018), resulting in an average specific power rating of 197 W/m^2 (down from 231 W/m^2 in 2018). However, while the trends in these parameters have been essentially linear in the past, one might reasonably argue that linear extrapolation is not appropriate going forward, given some of the significant challenges noted earlier—most notably, the square-cube law and the logistical and transportation-related constraints imposed by ever-larger blades (DNV GL 2019). These potentially binding constraints, which could restrict further increases in blade length, might suggest that the next concerted move in turbine scaling is more likely to come from the generator than the blades.

A similar view has recently been put forth by analysts such as Wood Mackenzie (2018), who expect the increasing adoption of competitive tenders for renewable energy worldwide, as well as the phase-out of the production tax credit (PTC) in the United States, to squeeze profit margins all along the value chain and drive the need for further turbine cost reductions in order for wind to remain competitive. Such cost reductions can potentially be achieved through additional economies of scale brought about by greater consolidation and standardization of global production lines toward the higher-capacity, higher-specific-power turbines favored in many other countries.[6] As a result of this view, Wood Mackenzie projects that the average capacity of wind turbines installed in the United States in 2025 will be 4.2 MW (significantly higher than the 3.0 MW derived from linear extrapolation), while average rotor diameter will increase to 155 m, resulting in an average specific power rating of 224 W/m^2—i.e., not significantly different from the 231 W/m^2 seen in 2018.

Recent product announcements from major wind turbine manufacturers also support this view. Over the past year, GE, Vestas, and Siemens Gamesa have all announced "next-generation" 5 MW platforms that feature specific power ratings of 255–270 W/m^2—i.e., significantly higher than 2018's average of 230 W/m^2.[7] This notable step up in specific power is driven entirely by the sharp increase in turbine capacity, as these turbines are generally using the longest blades that are currently available on the market (at least for land-based turbines).[8] As blade technology continues to advance, making even longer blades possible in the future, one can envision the specific power rating of these new platforms declining over time—just as it has in the past for earlier, smaller platforms, following what seems to be the normal product development cycle of initially boosting capacity and then letting rotors catch up over time. To that end, one of the three new product lines—GE's Cypress platform—is expected to mark the first widespread commercial use of segmented blades in order to achieve a 158 m rotor. This use of segmented blades is perhaps a harbinger of things to come, as transportation constraints for one-piece molded blades could become more and more binding (DNV GL, 2019).

Finally, at the other end of the spectrum, the U.S. Department of Energy's Wind Energy Technologies Office has its Big Adaptive Rotor (BAR) initiative, which seeks to realize the benefits of very low-specific-power turbines even among the next generation of higher-capacity turbines. Through a series of inter-related tasks (including one task that funded the research presented in this article), the BAR initiative is in the process of modeling innovative large blade design concepts that will enable a 5.0 MW reference turbine with a 206 m rotor and a specific power rating of 150 W/m^2—i.e., considerably below 2018's average specific power rating of 230 W/m^2, let alone the 255–270 W/m^2 range exhibited by the "next generation" 5 MW product launches mentioned above.

[6] In addition, to the extent that the PTC has been a driver of the adoption of low-specific-power turbines in the United States (see footnote 4), its loss removes that policy driver, perhaps narrowing the differences between the wind market in the United States and elsewhere.

[7] The extent to which these new 5 MW platforms are being marketed to projects in the United States is not yet clear; at present they could be more relevant to other markets. That said, Vestas has recently announced a handful of orders in the United States for turbines of 4.2 and 4.3 MW, suggesting that there is already some interest in larger turbines.

[8] For example, Vestas' online description of its EnVentus platform notes that the V162-5.6 MW turbine model "applies the largest rotor size in the Vestas portfolio to achieve industry-leading energy production paired with a high capacity factor." (https://www.vestas.com/en/products/enventus_platform/v162%205_6_mw#!v162-5.6-mw)

With such a wide range of options to consider—e.g., from the BAR initiative's 150 W/m^2 target to the 270 W/m^2 currently available in the 5 MW capacity range—we turned to geospatial modeling to quantitatively weigh the various trade-offs involved in such different design paths. Specifically, this section of the article relies on national supply curve modeling and CapEx sensitivities to further inform the economic opportunities associated with higher- and lower-specific-power wind turbines. The purpose is to illuminate those conditions under which lower- or higher-specific-power turbines may prevail in the future.

To quantify the change in capacity factor and LCOE associated with the turbine configurations studied, the analysis relies on hourly time series wind speed data from NREL's Wind Integration National Dataset (WIND) Toolkit.[9] The toolkit data can be briefly characterized as a national mesoscale wind-resource data set that includes meteorological data for more than 1.85 million locations in the contiguous United States. Each pixel in the data set reflects a 2-km-by-2-km grid cell. The toolkit provides 7 years of time series wind-speed data derived from model simulations of the weather patterns from the historical period of 2007–2013. These model simulations use real-world historical data to create synthetic representations of the mesoscale meteorological phenomena for the period of time from which the model input data are drawn. Although there are multiple hub heights available, we focus primarily on the data for 140 m (based on our turbine and hub height selections described below). Calculated capacity factors reported here reflect the multiyear mean capacity factor based on all 7 years of available WIND Toolkit data and include all pixels within the contiguous United States. This particular analysis does not consider exclusions of any particular location, even though there are areas where wind development is either unlawful (such as national parks) or impractical (such as very steep slopes and urban city centers).

As with all mesoscale data sets, there is uncertainty in the wind-speed data of the toolkit. This uncertainty is generally believed to increase at greater above-ground-level heights, where there has been less validation of the model output data. Accordingly, it is the *relative* differences in capacity factors and LCOE across the different turbine configurations, as opposed to the *absolute* capacity factor or LCOE values, that are of principal interest and focus in this analysis. Moreover, the geospatial results mapped in Figures 13 and 14 should be viewed for the general trends they illuminate as opposed to the precise spatial results that are associated with any single data pixel.

To estimate annual energy generation and gross capacity factors, the WIND Toolkit's hourly wind-speed data were applied to wind turbine power curves derived from the turbine configurations detailed in Table 2. Net capacity factors were estimated based on the application of a simple 16.7% loss adjustment. This adjustment has been used extensively in national supply curve characterizations by DOE and NREL (Cole et al., 2018; DOE, 2008; DOE, 2015b; Lantz et al., 2019; Stehly et al., 2017) and is intended to reflect a combination of array and electrical losses, as well as turbine downtime.

[9] The development of the WIND Toolkit (https://www.nrel.gov/grid/wind-toolkit.html) was funded by the Wind Energy Technologies Office within the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy, and was created through the collaborative efforts of NREL and 3TIER (which has since been acquired by Vaisala—http://knowledge.vaisala.com/3TIER, accessed September 1, 2019).

Table 2. Turbine configurations applied in national supply curve modeling

	2018 Average	Constant SP	Low SP	High SP
Nameplate Capacity (MW)	2.43	5.0	5.0	5.0
Rotor Diameter (m)	115.6	165.8	206	153.5
Hub Height (m)	88	140	140	140
Specific Power (W/m^2)	231.5	231.5	150	270

The turbine configurations shown in Table 2 are intended to be illustrative of current as well as potential future turbine specific power configurations. The *2018 Average* turbine is derived from the average statistics of turbines installed in the United States in 2018; it has a specific power of approximately 231 W/m^2. The *Constant SP* turbine scales the *2018 Average* to the same 5.0 MW capacity rating as the *Low SP* and *High SP* turbines, while holding specific power constant at the 2018 average of 231 W/m^2. The *Low SP* turbine has a specific power of 150 W/m^2, which is generally below the low end of the range of commercially available machines today (and well below that range if only considering larger, 5 MW platforms), but is consistent with the DOE BAR target. The *High SP* turbine reflects a 5.0 MW platform with a specific power of 270 W/m^2, which is generally commensurate with recent commercial offerings in this size class. With the exception of the *2018 Average* turbine being run at 88 m (to enable comparison against current technology), a single 140 m hub height was assumed for all analysis results.[10]

Figure 9 shows the absolute net capacity factor distributions for each of these four turbines across the United States, while Figure 10 shows the relative differences in these distributions, in this case, focusing on just the *Low SP* and *High SP* turbines relative to the *Constant SP* turbine.

[10] The 140 m hub height is, in part, based on ground clearance needs for 5 MW wind turbines fitted with the large blades necessary to achieve very low specific power (e.g., 150 W/m^2); it also offers the potential for additional capacity factor and LCOE gains (Lantz et al., 2019).

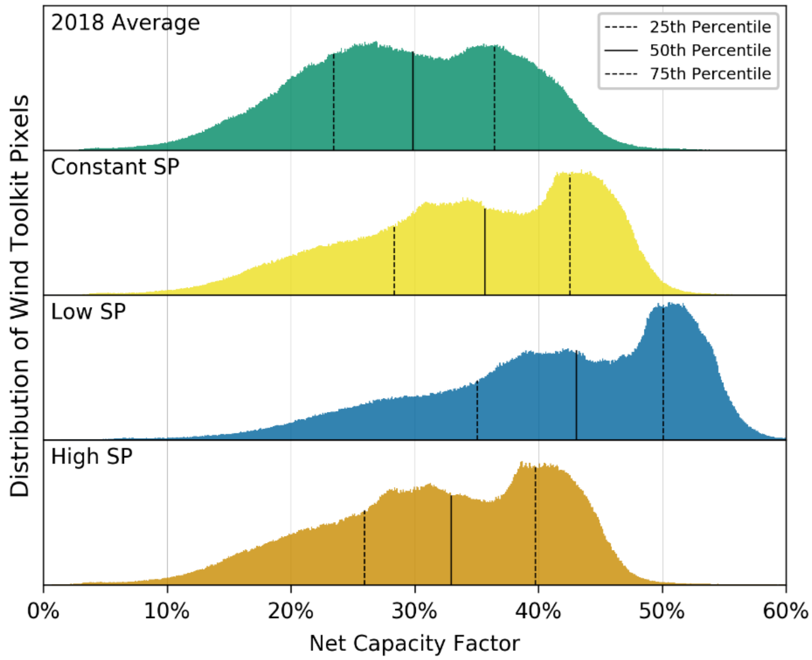


Figure 9. Net capacity factor distributions for each of the four turbines analyzed

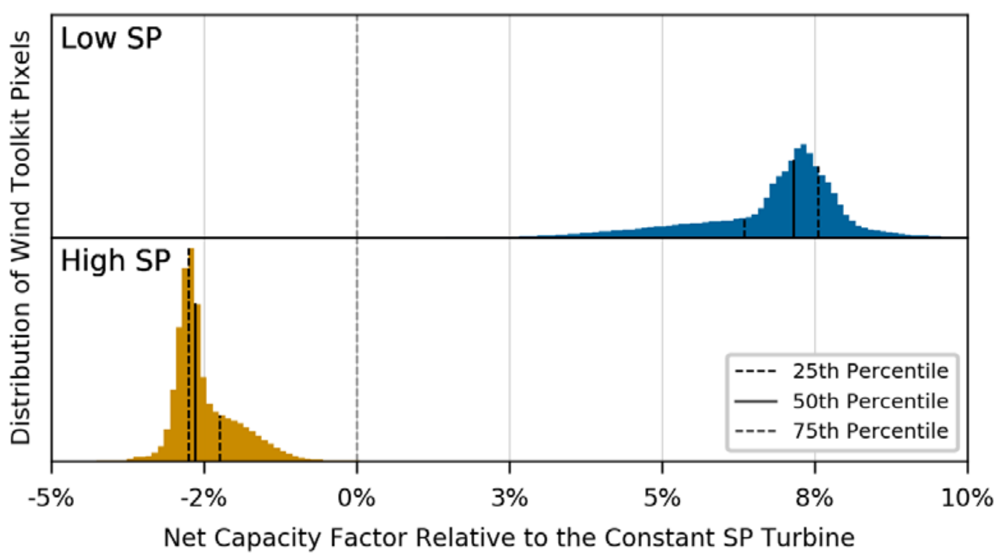


Figure 10. Net capacity factor of *Low SP* and *High SP* turbines relative to the *Constant SP* turbine

These data illustrate the potential gains in capacity factor that could be achieved relative to the *2018 Average* turbine (Figure 9) as well as differences in capacity factor among the 5 MW turbines due to having different specific power ratings (Figure 10). Not surprisingly, the *Low SP* turbine observes both the highest absolute capacity factors and largest relative gains. Although the *High SP* turbine sees a modest increase in median capacity factor (3 percentage points) relative to the *2018 Average* turbine, a small number of sites actually have *lower* capacity factors with the *High SP* turbine than with the *2018 Average* turbine. The median capacity factors for the *Low SP* and *High SP* turbines are approximately 7 percentage points greater than and 2 percentage points lower than the median value for the *Constant*

SP turbine, respectively (Figure 10). These data show that low-specific-power turbines could continue to provide substantial capacity factor and annual energy production gains into the future. Whether such turbines will become commonplace in the industry, however, will depend on their relative costs and value.

To evaluate the cost conditions under which higher- or lower-specific-power turbines might prevail, we constructed three simple cost-sensitivity scenarios—*Reference*, *Favor Low SP*, and *Favor High SP*. These scenarios are intended to highlight conceptual cost differences that could play out in the future (Table 3). Given that the focus of this analysis is on understanding the opportunity space for relatively lower- and higher-specific-power turbines, the *Constant SP* turbine maintains the same project-level CapEx value of $1500/kW—comparable to the average project-level CapEx estimate for 2018 as reported in Wiser and Bolinger (2019)—across all three scenarios.

Table 3. CapEx assumptions in each sensitivity scenario

	Low SP (2018 $/kW)	Constant SP (2018 $/kW)	High SP (2018 $/kW)
Reference	1620	1500	1380
Favor Low SP	1500	1500	1500
Favor High SP	1740	1500	1260

The *Reference* scenario generally aligns with traditional scaling theory—assuming equivalent site and design requirements—as well as the analytical and empirical cost estimates cited earlier (Bloomberg New Energy Finance, 2019; DOE, 2015b; Moné et al., 2015; Stehly et al., 2017; Wiser and Bolinger, 2019; Wiser et al., 2012), which hold that lower-specific-power turbines will have higher up-front costs (all else being equal). Informed by these prior estimates, this scenario pegs the *Low SP* and *High SP* CapEx at 8% above and below, respectively, the *Constant SP* CapEx. This results in a CapEx span of $240/kW between *Low SP* and *High SP*, which falls within the range of cost premiums suggested by prior analysis of blade scaling.

The *Favor Low SP* scenario holds CapEx constant at $1500/kW for all three turbine configurations, and therefore highlights how the differences in capacity factor shown above in Figures 9 and 10 would translate to LCOE, all else being equal. Although somewhat in conflict with traditional scaling theory (i.e., the square-cube law), this scenario is considered plausible for two primary reasons. First, turbine manufacturers can potentially influence and reduce costs through supply-chain optimization, including high-volume purchases. Second, higher-specific-power turbines designed to extract maximum energy from very strong and turbulent wind conditions could potentially require greater structural strength and, hence, ultimately more materials and mass, increasing their overall cost. The *Favor Low SP* scenario assumes that the *Low SP* turbine benefits substantially from supply chain optimization and volume, and therefore costs the same as the *Constant SP* turbine. Conversely, it also assumes that the *High SP* turbine that would be commercially available is penalized by increased strength requirements and low volume, and therefore loses any inherent cost advantage it might otherwise have (in theory) relative to the *Constant SP* turbine.

The final sensitivity, *Favor High SP*, was created for three specific reasons. First, we wanted to identify those conditions under which low- *and* high-specific-power technology prevail, and we know that to date, even with some empirical data points indicating modestly higher CapEx for low-specific-power technology (as reflected in the *Reference* scenario), these low-specific-power turbines have still tended to rapidly gain market share, particularly in markets with relatively fewer land constraints (e.g., United States, China, Brazil). Second, because the physics of scaling should tend to drive costs higher (all else being equal) for low-specific-power turbines and because there are additional potential system costs (e.g., in transport, towers, and foundations) that could be significant, we anticipate potentially more risk of cost escalation associated with lower-specific-power technology. Third, it is possible that turbine manufacturers operating in markets that are less capacity-constrained could develop the means to boost generator capacity at relatively low incremental costs (e.g., through software upgrades in the controls or power electronics) resulting in circumstances whereby the cost spread between lower- and higher-specific-power turbines, when denominated in $/kW, is relatively large. As such, in this scenario, we characterize the *High SP* turbine at a cost that is 16% less than the *Constant SP* turbine, while the *Low SP* turbine costs 16% more.

The next step in the analysis is to combine the CapEx estimates from Table 3 with the estimated capacity factors from Figure 9, along with fixed assumptions for total operational expenditures (OpEx) and financing terms, to estimate the LCOE. For total OpEx, we assume an estimated $41/kW-year, as informed by Wiser et al. (2019). For financing, we assume a real fixed charge rate of 8%,[11] commensurate with an implied nominal, after-tax weighted-average cost of capital of approximately 6.4%, and an implied real, after-tax weighted-average cost of capital of approximately 3.9%. Given our simplifying assumptions that OpEx and financing costs are constant across each turbine and scenario, these values affect the absolute, but not the relative, LCOE results.

Figures 11 and 12 present the distribution of LCOE and comparisons across turbine concepts and cost scenarios. Figure 11 holds CapEx constant across the three turbine configurations (i.e., reflective of the *Favor Low SP* scenario) in order to isolate the impact of capacity factor differences on LCOE, while Figure 12 highlights LCOE differences relative to the *Constant SP* turbine under all three CapEx scenarios.

[11] The fixed charged rate is a term that allows total CapEx to be annualized, considering the cost of capital (i.e., the weighted-average cost of capital) as well as the relevant tax treatment in terms of tax on assumed revenue and allowable depreciation.

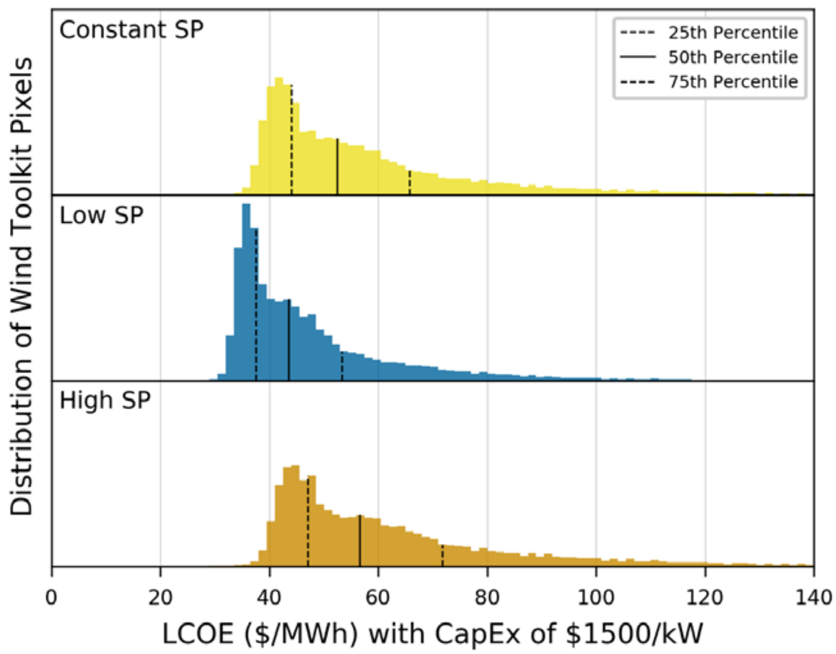


Figure 11. LCOE distributions among the turbines considered in the *Favor Low SP* scenario (i.e., assuming all three turbines have the same CapEx of $1500/kW)

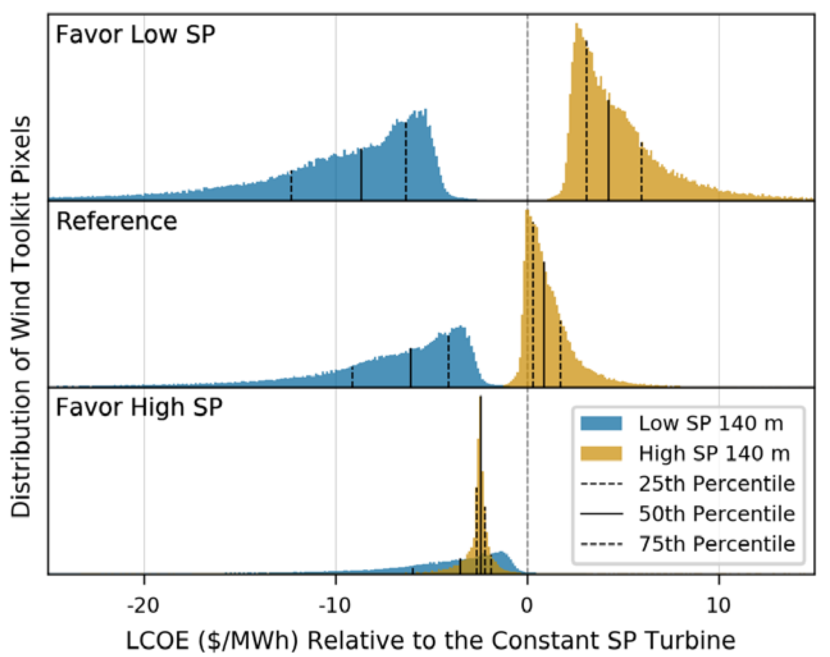


Figure 12. LCOE of *Low SP* and *High SP* turbines relative to the *Constant SP* turbine across the three CapEx scenarios shown in Table 3

Note: Each distribution reflects the same number of data points or pixels, even though the areas of the distributions within each scenario are scaled to show comparable maximum peak heights across scenarios

The absolute LCOE data from the *Favor Low SP* scenario (Figure 11) highlight potentially significant differences in LCOE solely as a function of the observed capacity factor differences. The *Low SP* turbine has the lowest overall LCOE value, with the highest quality resource sites achieving LCOE values that are less than \$35/MWh; moreover, the shape of the *Low SP* distribution results in greater clustering of geospatial pixels at the low end of the LCOE distribution. This drives a median value for the *Low SP* turbine of \$43/MWh as compared to \$52/MWh for the *Constant SP* turbine and \$56/MWh for the *High SP* turbine. Clearly, if CapEx were equal across these turbine options, as is assumed in the *Favor Low SP* scenario, preferences for low-specific-power technology would be high.

The relative outcomes across all three scenarios (Figure 12) suggest that the LCOE results and preferences for lower- or higher-specific-power technology are indeed sensitive to the cost conditions assumed. Under the *Favor Low SP* scenario, the preference for low-specific-power technology is likely to be strong in all locations, as described above. Under the *Reference* scenario, the distributions in Figure 12 are much closer together and the *High SP* turbine appears to be increasingly competitive with the *Constant SP* turbine. However, even under the *Reference* scenario, the *Low SP* turbine appears to almost universally have the lowest LCOE, indicating that for any given site, the *Low SP* turbine is likely to be preferred, all else being equal.[12] In this scenario, the median values for *Low SP* and *High SP* turbines are separated by about \$7/MWh. Under the *Favor High SP* scenario, the results are more even, with the *High SP* turbine having a lower LCOE than the *Constant SP* turbine in all locations, while also overlapping significantly with the *Low SP* turbine. In this scenario, the median LCOE values of the *High SP* and *Low SP* turbines are separated by only about \$2/MWh. Under these conditions, preferences for both turbines are likely to be meaningful, with the lowest-LCOE turbine determined largely by the site-specific characteristics of a given project.

While the absolute and relative LCOE distributions shown in Figures 11 and 12 provide a sense for the opportunities and challenges facing each turbine type under the three cost scenarios, Figures 13 and 14 illustrate *where* in the United States each turbine type is likely to find favor under two of these three scenarios,[13] by showing which turbine type has the lowest LCOE for a given geospatial pixel. In the *Reference* scenario (Figure 13), it is only the very highest wind resource sites—for example, along the mountain ridgetops in the West and East, where the capacity factor advantage of the *Low SP* turbine is partially eroded by increased time spent operating at rated power—that the *High SP* turbine prevails on the basis of LCOE. However, as we transition to the *Favor High SP* scenario (Figure 14), a CapEx tipping point occurs, whereby the *High SP* turbine wins out across much of the high-quality wind resource locations of the Central Plains and Upper Midwest.

[12] Of course, at sites that are highly turbulent or expected to have relatively extreme load events, higher-specific-power turbines designed for these harsher resource conditions may be preferred or required.
[13] Given that the *Reference* scenario is already almost entirely dominated by the *Low SP* turbine (as shown in Figures 12 and 13), there is no compelling reason to also map the *Favor Low SP* scenario.

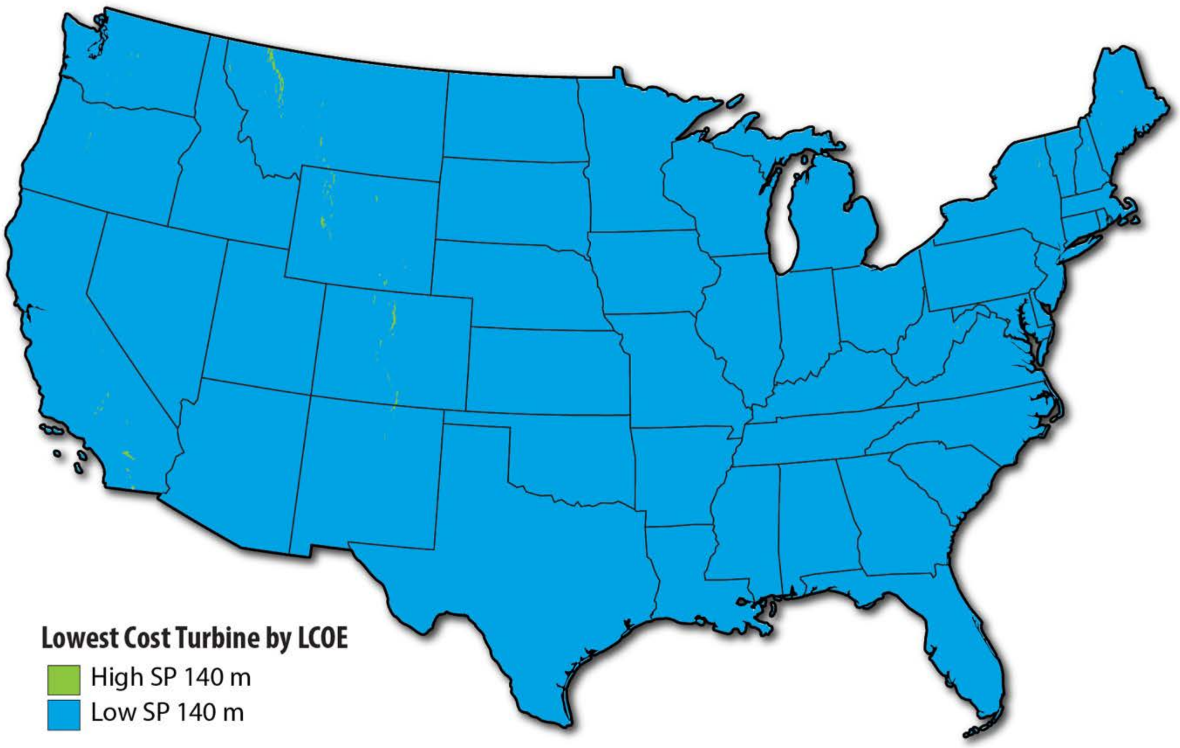


Figure 13. Lowest-LCOE turbine by location, *Reference* scenario

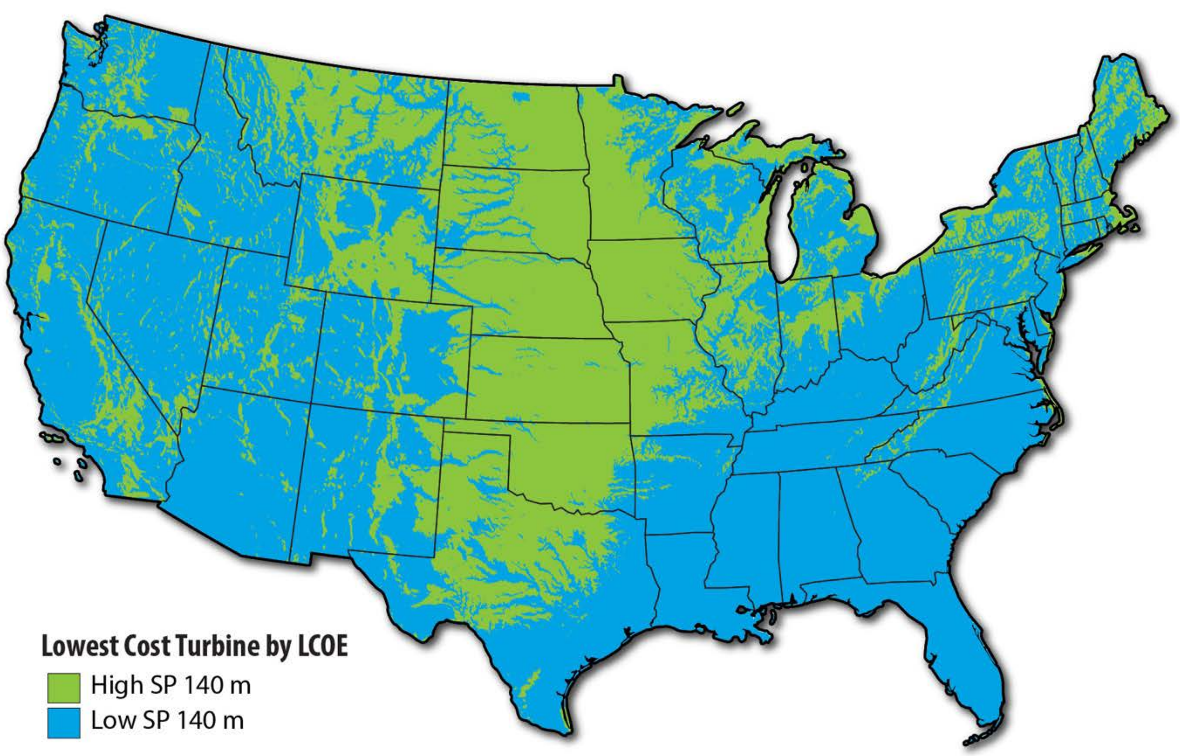


Figure 14. Lowest-LCOE turbine by location, *Favor High SP* scenario

Overall, Figures 11–14 suggest that there are conditions under which either low- or high-specific-power turbines could penetrate the market going forward. However, as long as the CapEx advantage for higher-specific-power turbines is approximately $240/kW or less, it is likely that lower-specific-power turbines will continue to support the lowest LCOE in virtually all locations where they can be suitably deployed. On the other hand, if the cost premium for low-specific-power turbines exceeds $240/kW, higher-specific-power turbines could become increasingly competitive, initially in very high wind resource sites but increasingly in moderate wind speed sites as well, particularly if the cost differential is at or in excess of $480/kW.

Within the context of the observed empirical trends described earlier, these modeling results suggest that real-world market conditions are perhaps most comparable to the *Reference* scenario, whereby there is meaningful competition between lower- and higher-specific-power turbines, but low-specific-power technology often wins. In this context, a competitive marketplace could be pushed further toward low-specific-power technology in places where there are capacity constraints, or alternatively toward higher-specific-power turbines where there are land constraints (and fewer capacity constraints). This observation could provide some insight into the overall global trends described earlier—i.e., toward lower specific power in general, but with certain land-rich but capacity-constrained markets like the United States and China pushing specific power ratings even lower.

For a final perspective on the relative economics of lower- versus higher-specific-power turbines, we turn to a metric known as the "breakeven cost," described by Lantz et al. (2019). In short, the breakeven cost equals the incremental CapEx premium or savings that a given turbine configuration (in this case, the *Low SP* and *High SP* turbines) would need to achieve at a given site in order to be competitive with a reference turbine (in this case, the *Constant SP* turbine) in terms of LCOE. Breakeven costs are a useful way to evaluate the magnitude of the potential challenge or opportunity associated with a given turbine configuration, without requiring a bottom-up cost estimate to compute actual competitiveness. In this case, the differences in capacity factors between the *Low SP* and *High SP* turbines relative to the *Constant SP* turbine (from Figure 10) are used to calculate the difference in CapEx—i.e., the breakeven cost—required for the *Low SP* and *High SP* turbines to achieve an equivalent LCOE as the *Constant SP* turbine.

Figure 15 shows the breakeven cost results. The capacity factor improvement offered by the *Low SP* turbine provides a significant margin—i.e., with a median exceeding $400/kW of incremental CapEx—for maintaining competitiveness with the *Constant SP* turbine. This breakeven cost is higher than even the upper end of the range of cost premiums incurred by low-specific-power turbines noted earlier, providing some justification for the historical deployment of such turbines.[14] Conversely, with a median breakeven cost approaching *negative* $150/kW, the *High SP* turbine must—due to its lower capacity factor—demonstrate sizable cost savings per unit capacity in order to be competitive with the *Constant SP* turbine on an LCOE basis. Of course, depending on the degree of innovation realized and potential scaling effects, costs for low-specific-power technology that exceed these breakeven levels are certainly possible, as are pathways that could enable relatively lower cost per kW values for higher-specific-power technology.

[14] That said, due to increasingly binding manufacturing and transportation constraints associated with larger blades, dropping from 231.5 W/m^2 to 150 W/m^2 (as reflected in the top pane of Figure 15) is likely to be more challenging from a cost perspective than was the same 81.5 W/m^2 decline from 313 W/m^2 to 231.5 W/m^2 (as reflected, at least generally, in the cost premiums incurred by low specific power noted earlier in this article).

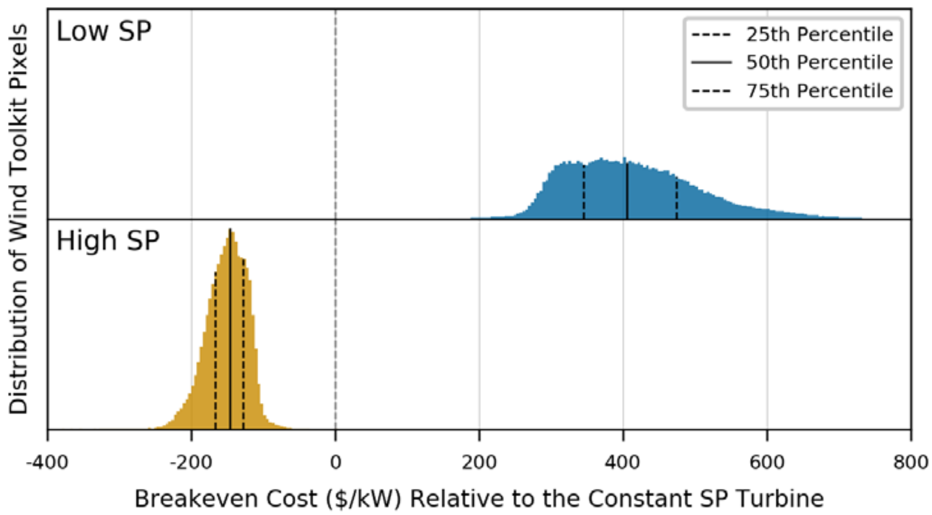


Figure 15. Relative change in CapEx that would result in an equivalent LCOE as the *Constant SP* turbine

Conclusions

The emergence and subsequent prevalence in many markets around the world of low-specific-power wind turbine technology over the past decade is a notable development and indicative of the rapid pace of technological advancement within the wind industry. In relatively capacity-constrained markets, lower specific power has been the most direct way to boost energy and revenue per invested dollar. In addition, lower specific power has supported large reductions in LCOE as innovation in blade design and materials has enabled turbine manufacturers to minimize scaling-related cost increases associated with larger rotors, thereby enabling the higher capacity factors of low-specific-power technology to translate into lower LCOE. Looking ahead, however, the future of low-specific-power technology is not altogether clear, as new commercial offerings with relatively higher specific power demonstrate that turbine design is a system optimization with competing objectives that may or may not drive toward lower specific power.

In this context, the geospatial analysis conducted herein suggests that under reasonable cost scenarios, low-specific-power turbines could continue to play an important role in U.S. and global markets going forward. Even under conditions that strongly favor high specific power (e.g., by penalizing low specific power by $480/kW), low-specific-power turbines could still be preferred (on economic grounds) in many moderate to low-wind-speed niches. At the same time, there are conditions under which a shift toward higher specific power could be anticipated, depending on the degree of cost savings per unit capacity offered by higher nameplate capacity turbines. Nevertheless, so long as the relative cost premium for low-specific-power technology can be restrained, and costs to boost generator capacity remain at or near current levels, the future for low-specific-power technology and large-rotor turbines more generally could be bright, especially as existing transmission capacity is increasingly consumed by wind plants or other generators, including solar photovoltaics. Of course, a key risk associated with lower-specific-power technology is the need to keep costs in check, particularly as turbine and blade designers must consider increasingly binding constraints in blade manufacture and transport.

Beyond these LCOE-based considerations, the boost in market value provided by low-specific-power turbines could also become increasingly important as wind penetration continues to grow. Further work examining this value boost from low-specific-power turbines at wind project sites across the United States is underway and is expected to provide greater insights on the relative economics of both large-rotor turbines generally and low-specific-power technology specifically. Other future work that could provide insights on optimal specific power is bottom-up techno-economic cost modeling focusing on the incremental system costs associated with rotor and generator scaling and considering the enhanced operational sophistication of modern turbine control systems. Such efforts could help to inform estimates of actual cost differences between lower- and higher-specific-power technology, the value of specific innovations that could affect specific power, and the potential trade-offs between turbines optimized for capacity- or land-constrained markets versus unconstrained turbines optimized to minimize LCOE.

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Declaration of Conflicting Interests

The Authors declare that there is no conflict of interest.

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